Collision warning dissemination in vehicles strings: an empirical measurement

Sébastien Demmel, Dominique Gruyer, Joëlle Besnier, Inès Ben Jemaa, Steve Pechberti and Andry Rakotonirainy

***Abstract*—Inter-Vehicular Communications (IVC) are considered a promising technological approach for enhancing transportation safety and improving highway efficiency. Previous theoretical work has demonstrated the benefits of IVC in vehicles strings. Simulations of partially IVC-equipped vehicles strings showed that only a small equipment ratio is sufficient to drastically reduce the number of head on collisions. However, these results are based on the assumptions that IVC exhibit lossless and instantaneous messages transmission. This paper presents the research design of an empirical measurement of a vehicles string, with the goal of highlighting the constraints introduced by the actual characteristics of communication devices. A warning message diffusion system based on IEEE 802.11 wireless technology was developed for an emergency breaking scenario. Preliminary results are presented as well, showing the latencies introduced by using 802.11a and discussing early findings and experimental limitations**

I. Introduction

COOPERATIVE collision avoidance is one of the prime application developed presently in the field of Intelligent Transportation Systems (ITS). In its most sophisticated form, it involves the exchange of positioning information between vehicles to anticipate future trajectories [1], [2] or infrastructure-based sensors [3]. The benefits of simpler forms of cooperative collision avoidance, or mitigation, based on the exchange of simpler warning messages have already been explored [4], [5]. Warning message can be sent from crashing vehicles to warn any following vehicle of the hazard. This warning can trigger an automated reaction or be displayed to the driver. In this paper, we present the design of a warning message system developed in order to show the limitations of using actual communications instead of simulated ones.

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The paper is organised as follows: in section II, we describe previous simulations, and their limitations, upon which this research expands. In section III, we present the experimental design (scenario and use case) and address the implementation of the "string" scenario with a set of equipped and non equipped vehicles. Section IV details preliminary results obtained over several on-track tests with 4-5 vehicles. Results cover 802.11a latencies and the measurement of vehicles' and drivers' behaviour. Limitations of the experimental protocol are discussed.

II. Rationale

A. Summary of our previous simulation experiments

This work is based on our previous studies examining the safety benefits of inter-vehicular communications (IVC) [4], [5]. They examined whether IVC could provide an answer to the safety-capacity trade off: how can the traffic density of already congested roads in modern urban agglomerations be increased without decreasing safety for drivers, considering no infrastructure modification. Another fundamental question they aimed at answering is the following: "*Which percentage of* [IVC] *equipment do we need to obtain a significant amelioration of the safety?*". The IVC equipment ratio will be labelled *p* henceforth.

A common simulation scenario is considered in our studies, which is labelled the "Brick Wall Scenario" [6]. It features a vehicles string, which leader has crashed against a stationary object (the hypothetical "brick wall") such as a stopped truck or a collapsed overpass or building. The following vehicles brake as soon as they become aware of the situation. They become aware thanks to their own embedded sensors (eyes in the case of human drivers, exteroceptive sensors for perception devices) or from a warning message broadcasted by the crashed vehicle.

Our first study [4] developed the concept of safety indexes based either on the number of collisions or the severity of collisions. The second index was found to be more relevant and less pessimistic than the former, because under the number of collisions-based safety index all collisions have an equal impact. However, collisions at lower relative velocities typically lead to less severe injuries and fatalities than collisions at higher velocities [6]. Nonetheless, for both indexes, it was found that IVC contributed to increase the string's safety.

Our second study [5] provided a more in-depth analysis of the equipment ratio influence on the vehicles string's safety. It remained within the context of the safety index based on the total number of collisions; different models for the distribution of intervehicular distances were studied. The study's simulation confirmed that only a small equipment ratio is necessary to drastically reduce the number of collisions. For example, at a capacity of 3,000 vehicles/hour and p = 5% the number of collisions is reduced by two third compared to an unequipped fleet. The best results were obtained with p = 25%, where the number of collisions was reduced by 90% (at higher capacities) and remained very stable for most simulated capacities.

B. *Overcoming the limitations of simulation studies*

While the benefits of IVC are stated clearly in our previously discussed work, a number of limitations surround this result. The main limitation is related to the communication modelling: vehicle-to-vehicle communications are assumed to be perfect. Although the drivers' reaction time is taken into account, so that the braking shock wave is moving between unequipped vehicles realistically, the initial collision warning broadcasted by the first vehicle is arriving at all equipped receptors instantaneously. Furthermore, no messages are lost or corrupted. The warning is then always correctly interpreted by the driver or by automated braking system. All IVC-equipped vehicles will thus start to break simultaneously, shortly after the warning message broadcast, whatever their position in the string, because they all share the same reaction time. Additional limitations are the identical characteristics of all vehicles (mass, braking capacity). These limitations are the consequence of the assumptions necessary to reduce the simulations' complexity.

Even if the simulation assumptions allow demonstrating the benefits of IVC, especially at small equipment ratios, these limitations preclude the scenario's transposition to actual vehicles strings. Indeed, communications latencies and variations in vehicles and drivers characteristics could negate the observed positive effects. One solution would be to increase the realism of the simulation by introducing a new communication model and a heterogeneous pool of vehicles. Another solution, which was chosen in this paper, is to perform empirical measurements with a set of IVC-equipped vehicles in a realistic driving environment. The goal of this "real-world" implementation is to validate IVC benefits in an imperfect environment. This approach allows us to take into account IVC-channel errors introduced by the driving environment such as multi-path fading or Doppler spread. This solution is preferred to additional simulations because it allows taking into account all possible imperfections. Indeed, using existing communication technologies will allow quantifying latencies and other errors introduced by real communications directly. Additionally, using real drivers and vehicles introduce heterogeneity in the string and allows considering the human-machine interface aspect.

III. Experimental Design

A. *Scenario requirements*

The experimental scenario is designed to reproduce as closely as possible simulations' conditions, presented in Section II-A, with the objective to compare and validate the results. A number of parameters must thus be considered: string's size, equipment ratio (p), distribution of equipped vehicles, interdistances, and the vehicles' velocity (kinematics).

1) *Total number of vehicles*

In our previous simulations, the vehicles strings were composed of large numbers of vehicles. For our experimental scenario, we limited ourselves to five research vehicles to demonstrate the scenario's feasibility. These research vehicles are all standard light passenger vehicles from French automotive manufacturers, modified to incorporate sensors and other active systems. In our scenario, most of the embedded instrumentation will not be used, unless it supports part of our system.

2) *Equipment ratio*

The currently available hardware does not allow for a fully equipped string (p = 100%). Nonetheless, results from [5] show that the number of collisions is most strongly reduced when p rises from 0 to 30%. For any greater p, the number of collisions remains stable. An additional data point at higher p is desirable, which is set at 60% (the highest equipment ratio achievable with the present hardware). This additional data point is used to verify that the experimental collisions number curve has the same envelop than the simulated one; p will thus take values 0, 10, 20, 30 and 60%.

3) *Repartition of equipped vehicles in the string*

Once their number has been set, IVC-equipped vehicles were positioned in the string. A uniform probability law is used to attribute an IVC system to each vehicle. This process is done simultaneously for all vehicles in the string and all the realisations without the appropriate p are rejected. The vehicle that triggers the collision warning is always considered to be an equipped vehicle; it is not accounted for in the aforementioned equipment ratio.

4) *Interdistances*

Interdistances between vehicles are a major factor that will influence the number of crashes in the string (due to reaction time). In [4] interdistances were modelled as constants noised by a centred Gaussian noise; in [5] three models were used: constant, exponential and truncated (strictly positive) Gaussian distributions.

The average interdistance d and road capacity c (the temporal definition of the string's density) are linked as shown in (1), where v is the string velocity and l the average vehicles' length [7].

$$c = v / \left(\bar{l} + \bar{d} \right) \quad (1)$$

The road capacity is a necessary parameter that was used in [4] and [5] to control the density of the vehicles string. However, in an experimental application of the vehicles string scenario, capacity is not an appropriate indicator. By controlling the string's average intervehicular distance, it is possible to approximate simulated capacities. If l = 4.002 m (based on the LIVIC & INRIA fleet), some interdistances and velocities necessary to reach the simulated capacities are shown in Table I. For example, if the string velocity is 90 km/h and the desired equivalent capacity is 2,000 vehicles per hour, the average interdistance must be 41 metres.

Velocity / Capacity	50	70	90	110	130
1800	23.78	34.88	46.00	57.12	68.22
2000	21.00	30.99	41.00	51.01	61.00
2500	16.00	23.99	32.00	40.00	48.00
3000	12.67	19.33	26.00	32.67	39.33

Table I. Interdistances computed from speed and capacity. Capacity in vehicles/hour, velocity in kilometres/hour and interdistance in metres.

These values represent the "ideal" target interdistances and cannot be maintained with such precision by drivers. An error range must thus be accounted for. In [5] the reduction of collisions by IVC was more important for higher capacities, which requires the shortest interdistances. This approach's limitations are discussed in section III-5.

5) *Vehicles positioning and safety margins*

Our scenario requires vehicles to brake in order to avoid impeding head-on collisions, but it is not possible for them to *actually* collide. IVC benefits are straightforwardly expressed by the decrease in collision count according to p. We must thus find a design that allows generating collisions while keeping test drivers safe. The best analogy to an emergency-braking vehicles string that we have found involves using an alternating formation (shown in figure 1). With vehicles positioned alternatively in two lanes, the interdistances between vehicles i and $i+1$ can be maintained at the required value while the actual distance between two vehicles *in the same lane* is twice the interdistance. Vehicles i and $i+1$ can virtually collide during the braking manoeuvre, when their longitudinal position intersect.

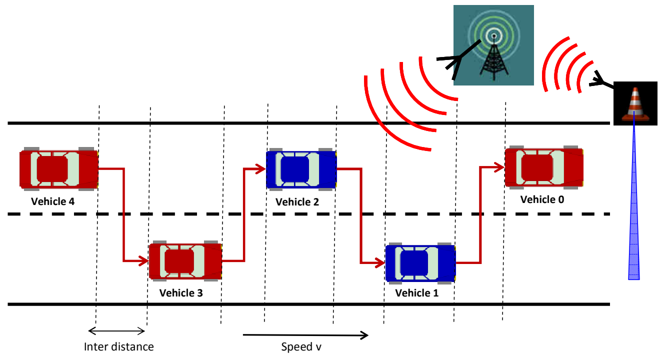

Fig. 1. Alternating formation for a safe experiment.

Virtual multi-vehicles collisions are even possible, although two vehicles in the same lane would stop too close from each other to guarantee safety. Dense strings might actually negate the security offset gained by using this formation. The residual distance d_r between two vehicles in the same lane is expressed as (2), with τ the driver reaction time.

$$d_r = 2(d - v\tau) \quad (2)$$

From (2) we can compute the safety margin for different velocities and interdistance; with τ set at 0.8 second. An interdistance of 30 metres becomes unsafe at 110 km/h, 20 metres becomes unsafe at 75 km/h. Thus, some of the velocity/interdistances combinations from table I cannot be implemented without risking real collisions. Furthermore, it is difficult for drivers to control precisely the interdistance with the leading vehicle. The alternating formation (figure 1) allows using visual hints such as the windshield beams, but without technological help the drivers will not be able to maintain a metric precision. Consecutively, drivers can only be asked to maintain an acceptable interval of interdistances, which in turns increase the necessary safety margin. This prompted us to use a laserscanner external device to measure the string interdistances for each scenario's iteration (as detailed in section III-C-2).

The alternating formation has some limitations. Since vehicle i driver is able to see vehicle $i+2$ braking lights, it is probable that its reaction time will be modified compared to a normally organised string.

6) *Road characteristics*

The scenario requires a long straight line so that the vehicles can organise themselves in the alternating formation and reach the appropriate interdistances. For additional details on the chosen location, refer to section III-C-3.

B. Simulation to measurements comparison criteria

The scenario's goal is to verify IVC benefits in an empirical setting. Two approaches can be followed. The first approach is to count virtual collisions at different values of p and compare the collision count's variation to match it with the simulated curve. The overall variation is compared rather than the absolute number of collisions. The second approach is to record the variation in the drivers' reaction times and braking patterns between equipped and non-equipped vehicles. This approach can be used a backup to validate IVC benefits if the first approach is not successful.

C. Equipment design and implementation

1) IVC warning system

The IVC warning system's architecture is presented in figure 2, organised in 3 blocks (represented by the dashed boxes) with the individual hardware and software components labelled. The top two blocks are used to simulate the string's first vehicle that broadcast the warning message with a fixed roadside unit (RSU). The top-right block is the main RSU block, housing the host computer and IVC device. The small top-left block is a dedicated component tasked with triggering the warning message broadcast. The lower block (labelled IV, for intelligent vehicle) describes each equipped vehicle.

The RSU and IV blocks use identical hardware and software. An *eBOX638* Linux embedded computer is hosting all applications and is connected by Ethernet networking to additional components:

- An IVC modem, labelled "IMARA box" to send or receive warning messages.
- A Network Time Protocol (NTP) server of the first stratum for time synchronization over the GPS signal.

Vehicles are also fitted with HMI devices (screens and sound devices) and an additional GPS for positioning purposes. The RSU main block includes a dedicated wireless receptor to receive the trigger signal, which is sent by a purpose-built traffic cone fitted with a small laser sensor (the top-left block in figure 2).

The IMARA box is an IEEE 802.11 multipurpose wireless modem designed by the INRIA and industrial partners, such as HITACHI, within the GEONET project [8]. The modems' geo-routing or 802.11p capabilities are not used in the present scenario: the modems are used to form a simple ad-hoc 802.11a network. Indeed, since vehicles will always remain in direct communication range from the emitter, there is no need for routing management. IPv6 is used instead of IPv4. The RSU modem is acting as a "master" for multicasting purpose, with all the vehicles members of the target group. Multicasting is the IPv6 equivalent of broadcasting in IPv4 [9]. When it receives a message from the *BreakAlert* RSU service, the master modem forwards this message to the target group. Routing is automatically handled; however, since the vehicles will always remain in close range to the RSU, all modems are in direct communication range with each others.

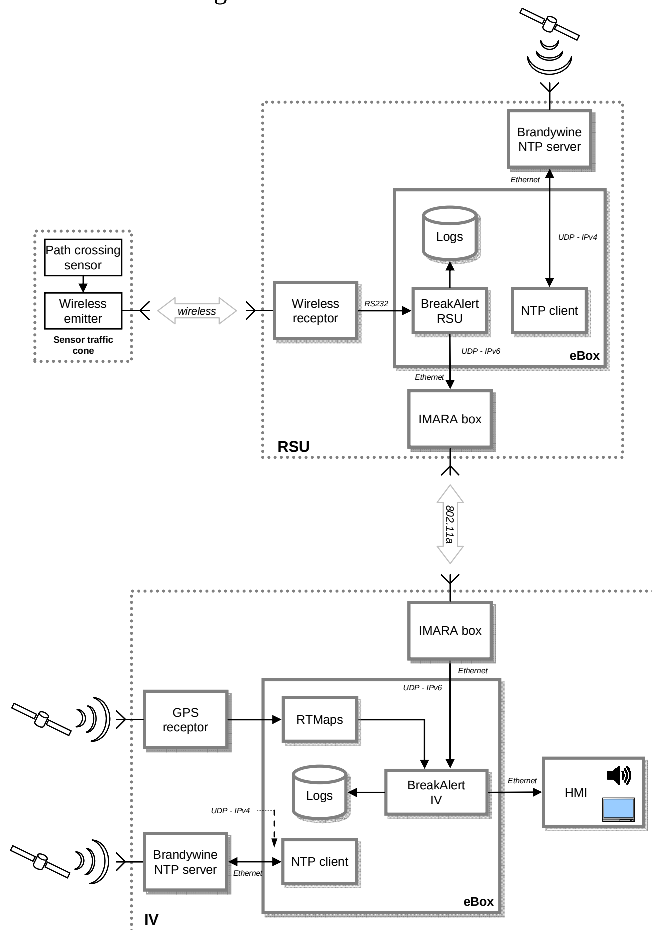

Fig. 2. System's architecture.

Our unified software architecture is based on the Extended Driver Awareness (EDA) framework, which was developed at LIVIC for the CVIS project [10]. EDA is a Java environment inside which dedicated software applications, labelled "services", can be developed. We chose to use this environment in order to benefit from the integration and automatic management of features such as networking sockets.

A *BreakAlert* service was developed. This service can be further subdivided into a RSU and an IV (Intelligent Vehicle) version. The two versions have identical code and are differentiated only depending on the accessible inputs. Indeed, in the RSU, the service is receiving prompts from the sensor-enabled traffic cone on a serial port and outputs in reaction a message on its Ethernet interface for the IMARA box. Meanwhile, in any vehicle, the service is still listening to serial port but will never receive the appropriate signal. On the other hand, a message addressed to it will arrive via the Ethernet interface from the IMARA box. This message triggers the display of a warning sign on the in-vehicle screen (figure 3). The drivers are instructed to perform an emergency braking as soon as they see this message or, if they are in an unequipped vehicle, as soon as they see the braking lights on the car driving in front of them *in the side line*.

Fig. 3. Warning message as displayed on the EDA human-machine interface.

BreakAlert logs all activity, allowing to track precisely all the latencies at various stages of a message progression. Timestamps of interest include: prompt on the serial port of the RSU; transmission of outbound message to the Ethernet interface; arrival of inbound messages at the Ethernet interface; and activation of the HMI. Some data are not accessible: (1) any latency within the traffic cone to RSU chain; and (2) latencies inside and between the IMARA boxes.

2) *Laserscanner device*

In order to precisely measure the position of all vehicles before, during and after the braking, an external laserscanner device is used. The laserscanner allows for a greater precision than in-vehicle GPS for such a relative positioning measurement. The device used is an IBEO LUX fusion system, fitted with two sensor heads. The LUX fusion system's output is recorded in RTMaps © on a separate computer, which is also using an NTP server to be synchronised with the IVC systems. Both raw and processed outputs are recorded for further post-processing.

3) *Test tracks*

Satory's test tracks have a speed track with a 2 kilometres-long straight line. The southern section of the road-like track (“*la routière*”) also has a 800 metres-long straight line. We found out that 800 metres is enough to form a five vehicles string. The speed tracks is impractical because the laserscanner used to measure interdistances does not have a large-enough field of view.

IV. Preliminary Results

We will now present some results obtained during a series of preliminary on-track tests at half the size of the expected full experiments. We used the same protocol and systems described in the previous section, the only difference being the reduced number of vehicles. These tests include 14 full iterations of the experimental scenario and additional IVC tests spread over 3 days in late 2010. These results, while of a limited scope, demonstrate the interest of implementing the vehicles string scenario.

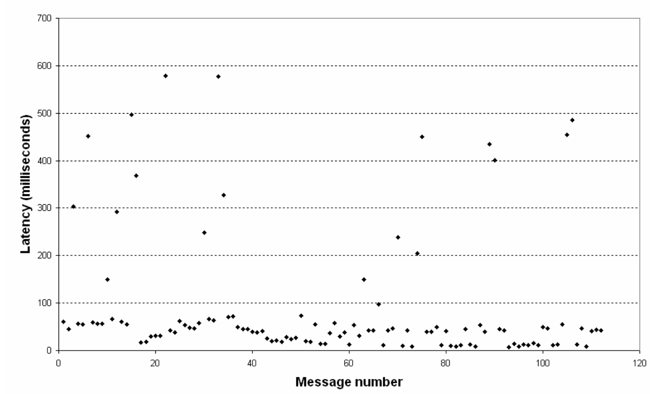

Fig. 4. Latencies recorded for 113 messages.

As discussed in section I, being able to evaluate the latencies, a major source of imperfection, was a major reason for the transposition of the vehicles string scenario to the “real-world”. The delay between the warning message broadcast at the RSU and reception at vehicles represents the largest part of the total latency chain. Figure 4 shows the latencies measured for 113 messages with the 802.11a implementation. The average delay is 46 milliseconds (geometric average), although 18 messages were delayed for more than 100 milliseconds; the sample's standard deviation is 141 milliseconds. It is unlikely that a model used to simulate delays, based on a Gaussian distribution, would have yielded these 10% of highly delayed messages. Typically, the chosen simulated standard deviation would have been smaller, given the scenario's specific conditions (close range, direct view). This result shows that empirical measurements are a significant improvement over previous simulations that do not account for delays. Further measurements will help fine tuning latencies models for future simulations. Furthermore, we expect 802.11p to significantly improve these delays, when implemented.

For the measurement of interdistances and braking patterns, typical results obtained from the roadside laserscanner sensor are shown in figure 5. The top graph shows the progression of each vehicle along the Y axis over time. Positions along the X axis do not need to be shown as the Y axis is parallel to the road; the X axis is only useful to differentiate between lines. The bottom graph shows the velocity of each vehicle, over the same time base. The three vehicles' formation is clearly visible, as well as the braking. In the shown recording, only three vehicles were used.

A major experimental limitation that emerged during preliminary tests is that it is difficult to actually obtain virtual collisions. Over 10 test drives with 4 vehicles, without communications, we only got 2 virtual collisions (and 2 close calls). Our preliminary assessment is that in the current experimental conditions, drivers are strongly expecting the braking event and their reaction time is considerably decreased. The average reaction time computed from the laserscanner data for these same ten test drives is 606 milliseconds, which is quicker than the average reaction time in more generic conditions [11]. Furthermore, all the used vehicles are recent models capable of strong emergency braking. These two effects compound to reduce the number of virtual crashes.

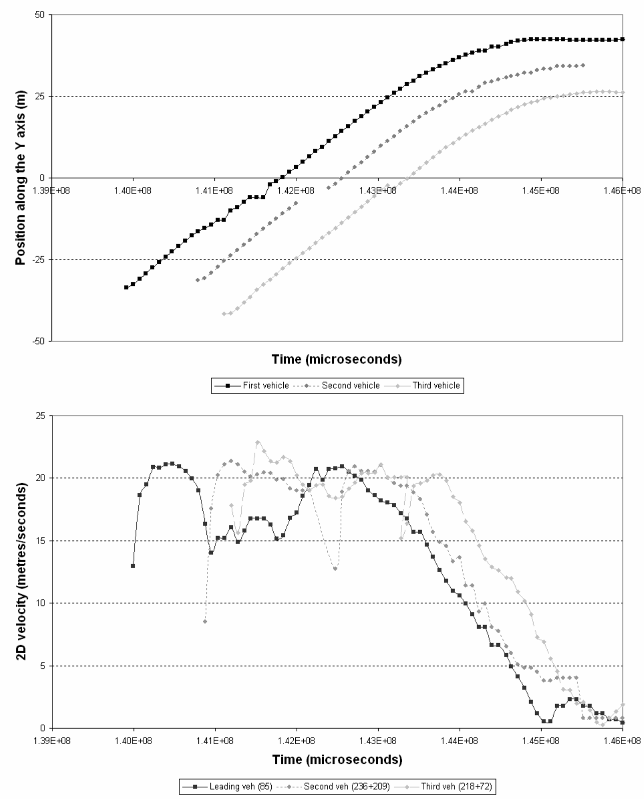

Fig. 5. Laserscanner measurements for a three vehicles string.

Nonetheless, some effect from the warning messages can be seen to emerge. Indeed, when comparing the average reaction time for two consecutive vehicles between test drives with and without *BreakAlert*, the average value decreases from 606 to 378 milliseconds. However, these results were obtained only from a limited number of experiments. Furthermore, it can be expected that all vehicles would brake within a brief time windows after receiving the warning message, with the time windows' size varying with the time necessary for drivers to become aware and react to the HMI warning. The present data do not allow determining whether this is the case or not.

V. CONCLUSION

The research design presented in this paper is an important step towards understanding and deploying full scale cooperative systems. We have designed an experimentation which allowed us to bridge the gap between theoretical simulation and empirical assessment. We have shown the feasibility of such bridging. Preliminary results do not allow yet validating or invalidating the simulations results; however, they show that with appropriate protocol modifications, it is probable that such a conclusion can be reached. Furthermore, measured latencies have shown unexpected results with a larger standard deviation that one could have expected given the experimental setting. This result will allow fine tuning any future simulation including latencies. A large scale implementation with ten or twelve vehicles is scheduled for the first semester 2011. Additional work will also focus on modifying this scenario to use automated braking. This solution would allow overcoming the limitations introduced by the drivers' reaction time.

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